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The Role of Preload Forces in Spinal Manipulation: Experimental Investigation of Kinematic and Electromyographic Responses in Healthy Adults

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Abstract

Objectives: Previous studies have identified preload forces and an important feature of skillful execution of spinal manipulative therapy (SMT) as performed by manual therapists (eg, doctors of chiropractic and osteopathy). It has been suggested that applying a gradual force before the thrust increases the spinal unit stiffness, minimizing displacement during the thrust. Therefore, the main objective of this study was to assess the vertebral unit biomechanical and neuromuscular responses to a graded increase of preload forces.
Methods: Twenty-three participants underwent 4 different SMT force-time profiles delivered by a servo-controlled linear actuator motor and varying in their preload forces, respectively, set to 5, 50, 95, and 140 N in 1 experimental session. Kinematic markers were place on T6, T7, and T8 and electromyographic electrodes were applied over paraspinal muscles on both sides of the spine.
Results: Increasing preload forces led to an increase in neuromuscular responses of thoracic paraspinal muscles and vertebral segmental displacements during the preload phase of SMT. Increasing the preload force also yielded a significant decrease in sagittal vertebral displacement and paraspinal muscle activity during and immediately after the thrust phase of spinal manipulation. Changes observed during the SMT thrust phase could be explained by the proportional increase in preload force or the related changes in rate of force application. Although only healthy participants were tested in this study, preload forces may be an important parameter underlying SMT mechanism of action. Future studies should investigate the clinical implications of varying SMT dosages.
Conclusion: The present results suggest that neuromuscular and biomechanical responses to SMT may be modulated by preload through changes in the rate of force application. Overall, the present results suggest that preload and rate of force application may be important parameters underlying SMT mechanism of action. (J Manipulative Physiol Ther 2014;37:287-293)
Key Indexing Terms: *Spinal Manipulation; Dose Response Relationship; Force; Electromyography; Kinematics, Manipulation; Chiropractic*

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The fundamental kinetic and kinematic parameters of spinal manipulative therapy (SMT) have been frequently studied, and parameters such as peak force, preload force, and time-to-peak force have been suggested as important features of SMT skillful execution. Chiropractic spinal manipulations are usually characterized by a high-velocity, low-amplitude (HVLA) thrust preceded by an initial gradual application of force commonly known as preload force.[1] Such progressive loading of spinal tissues (preload component of spinal manipulation) is believed to position the targeted vertebral segment near the limit of its physiological range of motion.[2,3] It has been suggested that gradually applying preload forces before the thrust increases the spinal unit (adjacent vertebrae together with connecting elements) stiffness, minimizing spinal displacement during the thrust phase of spinal manipulation.[4] A recent study indicates that a minimal preload force of 20 N increases paraspinal muscle activity until the thrust is applied.[5]

Most studies where spinal manipulations are performed by chiropractors do not report specific instructions or parameters related to preload force application.[2,3,6-11] However, given the large array of manipulative techniques combined with the complexity and diversity of vertebral unit structures throughout the spine, one should expect preload values to vary across patients, clinicians, and studies.[2,3,6-13] Indeed, for the cervical spine, various spinal manipulation techniques (lateral break, rotation, Gonstead technique, Activator technique, and toggle) were associated with preload forces ranging from 1.9 to 39.5 N.[8] Prone thoracic manipulations frequently used in experimental studies are also associated with a wide range of preload forces varying from 23.8 to 310 N (mean value, 123.6 N).[2,3,6,7,9-11,13] In the lumbar spine, 2 studies from Triano et al[14,15] looked at the biomechanical features of HVLA spinal manipulation but did not report any values for the preload forces, whereas a study on human cadavers used a mechanical device to perform spinal manipulations with predetermined preload forces of 0, 5, 10, and 20 N to emulate different degrees of patient positioning.[14,16] Finally, 2 studies investigated sacroiliac joint manipulations biomechanical parameters and reported values between 20 and 180 N for the preload force.[11,17] These results clearly highlight the wide range of preload forces selected by clinicians as well as researchers.

A recently published study investigated how SMT preload forces affect muscle spindle input from lumbar paraspinal muscles both during and after the SMT thrust in anesthetized cats.[18] The results showed that, when peak force and time-to-peak force remain constant, mean instantaneous discharge frequencies increased during SMT thrust phase compared with baseline. The amplitude of this increase seems to depend upon both preload amplitude and duration with no preload condition resulting in the greatest increase.

Nonetheless, there has not been, to our knowledge, any systematic investigation of preload forces parameters or any attempt at determining the physiological impact of this specific spinal manipulation component in healthy humans. Thus, the main objective of this study was to assess, in humans, the vertebral unit biomechanical and neuromuscular responses to a graded increase of preload forces. Based on previous results,[5] it was hypothesized that increasing levels of preload forces would yield a graded increase in vertebral movement and electromyographic (EMG) activity during the preload phase of spinal manipulation. It was also hypothesized that biomechanical and EMG responses during and after the thrust phase would proportionally decrease with increasing preload forces.

Methods

Twenty-three healthy subjects aged between 20 and 38 years old were recruited (mean age, 24.4 years; ±3.3). Participants who presented thoracic or lumbar pain, previous history of back trauma or surgery, severe osteoarthritis, inflammatory arthritis or vascular problems, or any other condition that would limit the usage of SMT were excluded from the study after a general examination performed by an experienced chiropractor. Those who were included gave their informed written consent according to the protocol approved by the University Ethics Committee (No. CER-12-181-06.37).

Experimental Protocol

To demonstrate the operation of the apparatus and its main security features, each participant was first shown a demonstration of a simulated spinal manipulation performed by the apparatus. Each participant then lied down in a prone position on a chiropractic table. Electromyographic electrodes were applied over paraspinal muscles (right and left longissimus thoracis, T6 and T8 levels) following fiber orientation and kinematic markers were positioned on the spinous process of T6, T7, and T8. All participants underwent 4 different SMT force-time profiles characterized predetermined preload force for the first 750 milliseconds followed by an impulse phase of 125 milliseconds leading to a peak force of 300 N. The 4 SMT force-time profiles differed in their preload forces (not duration), respectively, set to 5, 50, 95, and 140 N. A 5-minute pause was taken between each trial, and the various preload conditions were randomized across participants to avoid any sequence effect.

Apparatus

Electromyographic activity was recorded using a Delsys Surface EMG electrode with a common mode rejection ratio of 92 dB at 60 Hz, an input impedance of 1015 Ω (Model DE2.1; Delsys, Inc, Boston, MA). Electrodes were applied over the thoracic spine erector spinae muscles on each side of the spine, approximately 2 cm from the T6 and T8 spinal processes. Thus, 2 electrodes were placed on both right and left sides of T6. The reference electrode was positioned on the left acromion of each participant. For each electrode, (1) the desired body part (region) was gently shaved, (2) then the skin was gently abraded with fine-grade sandpaper (Red Dot Trace Prep; 3 M, St Paul, MN) and finally (3) skin was wiped with alcohol swabs. These 3 steps were systematically done for each electrode for each participant to reduce skin impedance. Data were sampled at 1000 Hz with a 12-bit A/D converter (PCI 6024E; National Instruments, Austin, TX). The data were collected by LabView (National Instruments) and processed by Matlab (MathWorks, Natick, MA). A motion analysis system (Optotrak Certus; Northern Digital, Waterloo, Ontario, Canada) was used to perform the kinematic data acquisition. Kinematic markers were

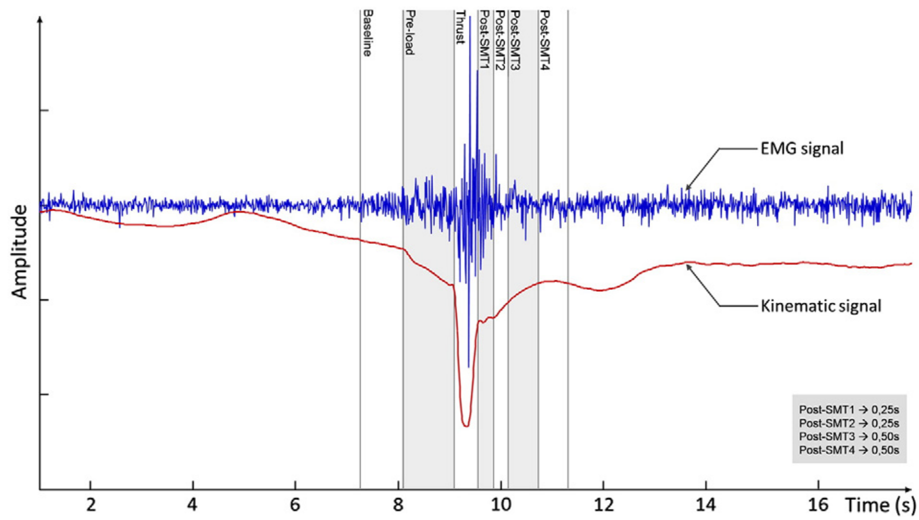

Fig 1. *Typical EMG and kinematic responses throughout the various SMT time windows defined in the Methods section. (Color version of figure is available online.)*

placed on T6, T7, and T8 spinous process, and data were collected at 100 Hz.

A servo-controlled linear actuator motor (Linear Motor Series P01-48x360; LinMot, Inc, Zurich, Switzerland) was developed and used to precisely simulate SMT for the 4 different preload forces. The linear motor vertically displaced a slider applied directly to the spine. A padded rod serves as the contact point between the servo-controlled linear actuator motor and the spine (T7). A microcontroller accurately controlled the linear motor to reproduce a target SMT force-time profile loaded from a computer; a close loop force constantly providing the needed intensity to the motor to obtain a measured force as close as possible to the target force. A complete technical description and details of the safety features are presented elsewhere.[19]

Data Analysis

Electromyographic data were filtered digitally by a 20 to 450 Hz band-pass fourth-order Butterworth filter. A band-stop fourth-order Butterworth filter was also applied to remove power line interferences (60 Hz and its harmonics). To analyze EMG responses according to SMT force events, 7 time windows (see Fig 1) that spanned across the entire SMT force curve were defined: "Baseline" of 0.5-second duration to observe EMG activity before the SMT, "Preload phase" of 1 second, the "Thrust phase" of 250 milliseconds, and 4 phases that successively followed the "Thrust phase" with 2 windows of 250 milliseconds and 2 windows of 500 milliseconds (referred as post-SMT1 to post-SMT4 as illustrated in Fig 1). For each trial, the 4 EMG recordings were divided in 7 normalized root mean square (RMS) values corresponding to each time windows. Raw normalized RMS values were obtained by dividing each RMS value by the RMS value obtained during the "preload phase." Three different kinematic variables based on 3 specific time windows were considered in the study: vertebral displacement from baseline to preload, from preload to thrust and from baseline to thrust. A posterior to anterior force vector was used to perform spinal manipulations, and sagittal plane displacements were calculated. These values were calculated for the three kinematic markers on T6, T7, and T8.

Statistical Analyses

All dependent variables (normalized RMS values and kinematics) were found to be normally distributed and were submitted to 1-way repeated-measures analysis of variance (ANOVA) (4 different preload levels). Whenever ANOVA yielded a significant time effect, polynomial contrasts were conducted to test for the linear trend (linear relationship between preload force applied and EMG response). Polynomial contrasts provide the opportunity to look at the response curve of the data and determine the nature of the relationship between SMT and EMG responses. The level of statistical significance was set at $P < .05$ for all analyses.

Results

Figure 1 illustrates typical kinematic and EMG responses to a given SMT force-time profile. Overall, modulating the preload forces (5, 50, 95, and 140 N) led to

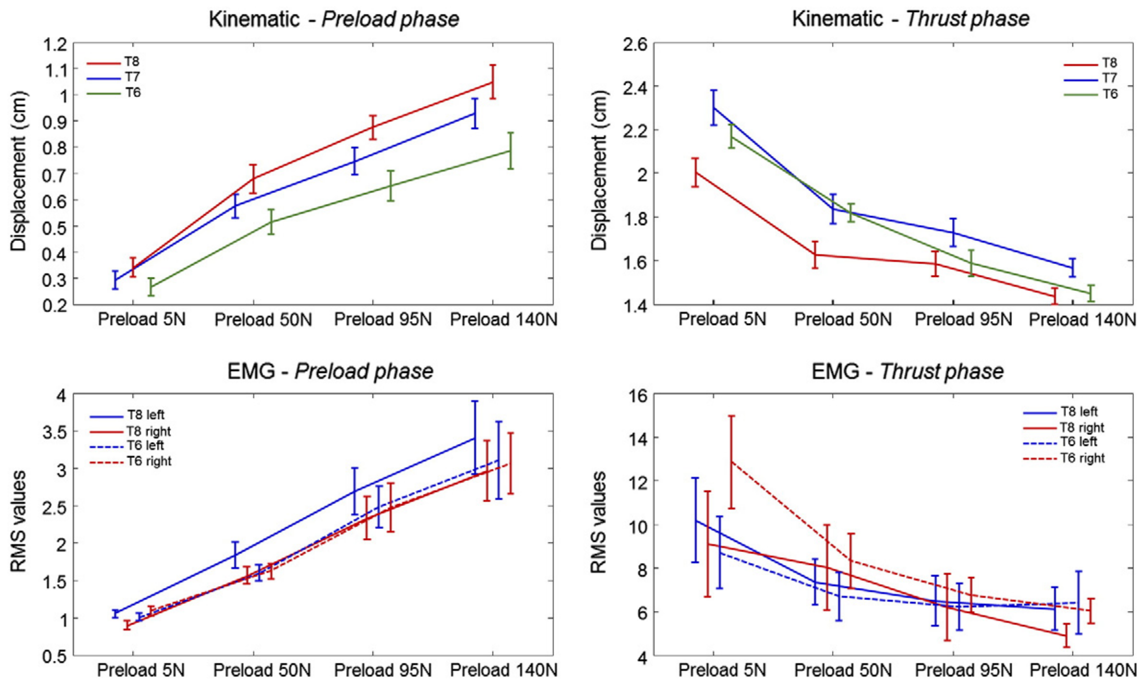

Fig 2. *Kinematic and EMG responses to varying levels of preload during the preload and thrust phases. Sagittal displacements of T6, T7, and T8 as well as normalized RMS values (T6 left and right, T8 left and right longissimus thoracis) during the preload and thrust phases are presented. (Color version of figure is available online.)*

significant differences in both kinematics and paraspinal EMG during the preload phase but also during the thrust phase and the first postthrust time window. Precisely, the 1-way repeated-measures ANOVA (4 levels of preload force) showed that increasing the preload force led to a significant increase in sagittal vertebral displacement and paraspinal muscle activity during the preload phase of spinal manipulation (all $P < .001$). Alternatively, increasing the preload force yielded a significant decrease in paraspinal muscle activity during the thrust phase of spinal manipulation (all $P < .02$) and the first time-window (SMT-1) following the thrust (all $P < .05$). Sagittal posterior to anterior vertebral displacements also decreased with increasing preload forces (all $P < .001$). Kinematic and EMG responses to varying levels of preload during the preload and thrust phases are presented in Figure 2. Paraspinal EMG activity was similar across all preload conditions during the baseline time-window as well as during post-SMT2 (with the exception of T6 right where a significant difference was observed), post-SMT3, and post-SMT4 time-window indicating that changes in preload forces did not affect muscular activity during these components of spinal manipulation ($P > .05$). Total vertebral displacements (baseline to thrust) were also similar for all preload conditions ($P > .05$). Tables 1 and 2, respectively, present the mean (SD) normalized RMS values and vertebral displacement during the preload, thrust, and postthrust time interval (post-SMT 1-4).

Discussion

The goal of the present study was to determine the biomechanical and neuromuscular responses to increasing preload forces using a servo linear motor designed to emulate spinal manipulation in humans. The results indicate that EMG responses of thoracic paraspinal muscles and vertebral displacements are linearly correlated to the level of force applied during preload, whereas EMG responses and segmental displacements during and after the thrust phase decrease with increasing preload forces. Such results indicate that force application before the HVLA component of spinal manipulation can modulate physiological responses to SMT and may potentially modify clinical responses. There is limited knowledge regarding the influence of preload force on segmental biomechanics and EMG responses during SMT, and although indication of preload force applied during SMT can be found in the literature, the effect of varying levels of preload has rarely been investigated. Indeed, Reed et al[18] showed that the variation of preload amplitude and duration significantly modifies mean instantaneous discharge frequencies of muscle spindle during the spinal manipulation thrust. Smaller preload amplitude (18% of peak force) and longer preload duration (4 seconds) resulted in the greatest increase compared with larger preload amplitude (43% of peak force) and shorter preload duration (1 second). Our data suggest a similar association between preload

Table 1. *Mean (SE) of Normalized RMS Values During the Preload, Thrust, and Postthrust Time Interval (Post-SMT 1-4)*

EMG	Preload (N)	Baseline	Preload	Thrust	Post-SMT1	Post-SMT2	Post-SMT3	Post-SMT4
T8 left	5	1.01 (0.05)	1.06 (0.05)	10.19 (1.94)	4.61 (1.35)	2.53 (0.71)	1.86 (0.54)	1.36 (0.33)
	45	1.11 (0.07)	1.84 (0.17)	7.35 (1.05)	3.39 (0.67)	2.06 (0.31)	1.42 (0.27)	1.36 (0.26)
	90	0.96 (0.04)	2.69 (0.32)	6.51 (1.13)	2.45 (0.31)	1.66 (0.25)	1.26 (0.17)	1.14 (0.15)
	135	0.92 (0.05)	3.41 (0.48)	6.13 (0.98)	3.28 (0.79)	1.77 (0.36)	1.33 (0.29)	1.21 (0.23)
	P	.183	<.001	<.001	.023	.135	.277	.670
T8 right	5	0.92 (0.05)	0.90 (0.06)	9.11 (2.41)	4.21 (0.96)	2.34 (0.50)	1.71 (0.44)	1.35 (0.38)
	45	1.07 (0.08)	1.57 (0.12)	8.04 (1.95)	2.71 (0.34)	1.80 (0.26)	1.36 (0.20)	1.14 (0.13)
	90	0.98 (0.05)	2.34 (0.29)	6.21 (1.51)	2.18 (0.26)	1.57 (0.17)	1.12 (0.08)	1.03 (0.08)
	135	1.02 (0.08)	2.97 (0.40)	4.90 (0.54)	2.33 (0.29)	1.76 (0.27)	1.31 (0.17)	1.27 (0.18)
	P	.56	<.001	.02	<.001	.05	.29	.65
T6 left	5	1.06 (0.05)	1.01 (0.05)	8.70 (1.64)	4.62 (1.32)	2.53 (0.60)	2.19 (0.70)	1.52 (0.34)
	45	1.09 (0.06)	1.60 (0.10)	6.71 (1.11)	3.54 (0.80)	2.48 (0.55)	1.68 (0.30)	1.81 (0.42)
	90	0.94 (0.04)	2.49 (0.28)	6.24 (1.09)	2.62 (0.30)	1.76 (0.33)	1.46 (0.30)	1.42 (0.26)
	135	0.91 (0.04)	3.11 (0.05)	6.42 (1.43)	3.10 (0.82)	1.91 (0.37)	1.41 (0.23)	1.30 (0.21)
	P	.07	<.001	<.001	.04	.09	.25	.18
T6 right	5	0.98 (0.04)	1.09 (0.07)	12.85 (2.11)	4.45 (1.00)	2.63 (0.52)	1.98 (0.50)	1.61 (0.35)
	45	1.06 (0.05)	1.63 (0.10)	8.32 (1.26)	3.54 (0.70)	1.80 (0.20)	1.40 (0.19)	1.24 (0.17)
	90	0.97 (0.04)	2.47 (0.33)	6.78 (0.82)	2.57 (0.26)	1.64 (0.22)	1.15 (0.10)	1.05 (0.08)
	135	0.98 (0.05)	3.07 (0.41)	6.04 (0.55)	2.62 (0.31)	1.62 (0.23)	1.24 (0.14)	1.15 (0.13)
	P	.56	<.001	<.001	.01	.01	.06	.10

amplitude and paraspinal muscle activity during spinal manipulation and may suggest that these increases in paraspinal muscle activity result from an increase in muscle spindle discharge during thrust application. However, the observed increases in spindle discharge and muscle activation following lower levels of preload forces may appear unexpected given the muscle spindle thixotrophy phenomenon, which can be defined as the modification of muscle spindle physical properties following a mechanical perturbation.[20] This phenomenon suggests that further lengthening of a lengthen muscle spindle results in an increase in the muscle spindle discharge; thus, increasing preload amplitude would have resulted in the increase of paraspinal muscle activity during the thrust component of spinal manipulation. As proposed by Reed et al,[18] modifications in muscle spindle discharge may be explained by changes in thrust rate of force application (the higher the preload force, the lower the rate of force application). Their results are supported by previous studies that reported similar increases in muscle spindle and EMG activity of paraspinal muscles during increasing levels of force and vertebral displacement during the thrust phase of SMT.[5,21] The present results can, therefore, be compared with those obtained in animal models and human studies aim at evaluating rate of force application. Reed et al[21] showed that muscle spindle discharge increased with thrust rate in a nonlinear fashion. In the present study, where the rate of force application reached values as high as 2360 N/s, EMG RMS values decreased linearly with increasing preload forces (ie, decreasing thrust rate of force application). In brief, preload force seems to modulate paraspinal muscle activity prior and during the thrust component of SMT. Neurophysiological changes observed during SMT may operate through changes in the rate of force application, but interactions between preload forces and rate of force application remain to be investigated. Because total vertebral displacements (baseline to thrust) were constant throughout all preload conditions, the current results also suggest that biomechanical responses to SMT appear to be related to the total amount of force applied to the spine (force applied during preload + force applied during the thrust). Indeed, vertebral movement occurred during the slower spinal deformation generated by preload during which tissue resistance to movement is less important. Additional forces applied to the spine during the thrust, despite increased stiffness and rapid deformation, also generate significant vertebral movement. These vertebral movements represent global anterior to posterior spinal deformation and 3-dimensional relative movement between vertebrae may respond differently following preload force application.

Study Limitations

The physiological responses to preload forces described in the present study were obtained from young healthy participants and may not be generalizable to other populations, including patients with spinal pain or spinal degeneration. During testing, occlusion of kinematic markers led to loss of data at T6 during the thrust phase for some participants. Although significant differences in T6 vertebral displacement were observed, improvements of

Table 2. *Mean (SE) of Posterior to Anterior Vertebral Displacement (Centimeter) During the Preload, Thrust Phase of SMT*

Markers	Preload (N)	Preload Phase	Thrust Phase
T8	5	0.29 (0.035)	2.00 (0.07)
	45	0.58 (0.05)	1.63 (0.07)
	95	0.75 (0.06)	1.59 (0.06)
	140	0.93 (0.06)	1.44 (0.04)
	P	<.001	<.001
T7	5	0.34 (0.04)	2.30 (0.09)
	50	0.68 (0.06)	1.84 (0.07)
	95	0.88 (0.05)	1.73 (0.08)
	140	1.05 (0.07)	1.57 (0.04)
	P	<.001	<.001
T6	5	0.27 (0.04)	2.17 (0.08)
	50	0.51 (0.05)	1.82 (0.06)
	95	0.65 (0.06)	1.67 (0.08)
	140	0.79 (0.08)	1.46 (0.05)
	P	<.001	<.001

the experimental setup are needed before other vertebral movements such as rotation or lateral flexion are studied. Electromyographic response latencies should also be studied to determine the effect of preload forces on spinal and supraspinal responses to SMT.

Clinical Implications and Future Studies

The modulation of neuromuscular and kinematic responses to SMT thrust could be explained by the proportional increase in preload force or the related changes in rate of force application that have both been suggested as potential SMT parameters driving the physiological and perhaps the clinical responses to spinal manipulation. From a clinical perspective, the present results indicate that increasing preload forces will lead to increased spinal stiffness and, consequently, impact the spinal segment resistance to movement during the thrust. Clinicians should, therefore, consider the preload phase in the delivery of care. Fundamental and clinical investigations of SMT dose-physiological response relation in humans are needed to clarify the specific impact of preload force modulation. Future studies should investigate the clinical implications of varying SMT dosages.

Conclusion

Preload forces modify vertebral displacement and paraspinal muscle activity throughout various phases of SMT. The present results suggest that neuromuscular and biomechanical responses to SMT may be modulated by the rate of force application. Although only healthy participants were tested in this study, one could argue that preload and rate of force application may be important parameters underlying SMT mechanism of action.

Practical Applications

- Preload forces are characteristics of HVLA spinal manipulation.
- This study investigated how varying levels of preload force applied during spinal manipulation can modify local muscle activity and kinematic responses.
- Increasing the preload force leads to a significant increase in sagittal vertebral displacement and paraspinal muscle activity during the preload phase of spinal manipulation.
- Moreover, increasing the preload force leads to a significant decrease in sagittal vertebral displacement and paraspinal muscle activity during the thrust phase of spinal manipulation.

Funding Sources and Potential Conflicts of Interest

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Contributorship Information

Concept development (provided idea for the research): MD.
Design (planned the methods to generate the results): MD, CD, FN.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): MD, CD.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): FN, ML, IP.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): MD, CD, FN.
Literature search (performed the literature search): MD, ML, IP.
Writing (responsible for writing a substantive part of the manuscript): MD, CD, FN, IP.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): MD, CD.
Other (list other specific novel contributions): ML (recruitment).

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